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Increasing the Micromechanical and Tribological Characteristics of an Austenitic Steel by Surface Deformation Processing

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Abstract. Frictional treatment (FT) with a sliding indenter forms highly dispersed (nano- and submicrocrystalline) austenitic structures with a hardness of 720 HV 0.025 in the surface layer of the 03Cr16Ni14Mo3Ti austenitic strain-resistant steel. According to the data on microindentation, FT increases the strength and of the surface layer of the austenitic steel and its resistance to elastic and plastic deformation. A high effectiveness of FT in the improvement of the tribological properties of the steel is demonstrated; namely, wear resistance increases 4 times under conditions of boundary friction as compared to the undeformed state. This is due to reduced plastic edging on the nanostructured surface.

INTRODUCTION

High corrosion resistance and workability of austenitic chromium-nickel steels are determinant when they are selected as structural materials in various industries. Austenitic steels remain corrosion-resistant in sea water, in a humid environment and in aggressive media; however, they have low wear resistance and strength characteristics, and this limits their application considerably.

Nanostructuring FT with a sliding indenter is an effective method for improving the strength and tribological properties of Cr-Ni metastable austenitic steels with 8.44 to 10.04% Ni [1-3]. It is of interest to discuss the features of FT of austenitic steel with a high nickel content (14.17%), which makes austenite resistant to the strain-induced $\gamma \rightarrow \alpha'$ transformation, since the presence of strain-induced martensite in the surface layer may have an unfavorable effect on the corrosive characteristics of the steel [4]. The aim of this paper is to study the effect of FT with a sliding indenter on the structure, phase composition, micromechanical and tribological characteristics of the surface layers of the 03Cr16Ni14Mo3Ti austenitic stainless steel.

EXPERIMENTAL PROCEDURE

The 03Cr16Ni14Mo3Ti corrosion resistant austenitic steel was studied, its composition being as follows (wt%): 0.03 C, 15.69 Cr, 14.17 Ni, 1.17 Ti, 0.25 Mn, 0.64 Si, 2.67 Mo, 0.03 Co, 0.004 Nb, 0.11 Cu, 0.030 P, 0.008 S, 0.043 V, and the rest Fe. Specimens sized 36×36×6.5 mm were subjected to water quenching from 1100 °C, mechanical grinding and electrolytic polishing (EP). FT was performed with a hemispherical synthetic diamond indenter, with the hemisphere radius $R=3$ mm, in the non-oxidizing argon environment, with a load on the indenter $P=294$ N, the mean velocity of the reciprocating indenter $V=0.05$ m/s, the scan length $l=29$ mm, with a 0.1 mm

displacement of the indenter per each double scan and the number of scans $n=7$. The use of a synthetic diamond indenter and the argon environment during FT provides severe strain hardening of metastable austenitic Cr-Ni steel in the absence of adhesive seizure typical of FT with indenters made of a W-Co hard alloy and finely dispersed boron nitride even in case a coolant is used [5].

Tribological testing was performed under conditions of sliding friction according to the pin-plate scheme on 03Cr16Ni14Mo3Ti steel specimens with a working area of 5.5×5.5 mm reciprocating on a 45 steel plate (50 HRC) with lubrication (I-30 industrial oil), under the loads $P=392$ and 588 N, with the average sliding velocity $V=0.07$ m/s, the friction path $L=160$ m, the travel length $l=40$ mm. Wear intensity I_h was calculated by the formula $I_h = \Delta m / (\rho SL)$, where Δm is specimen mass loss, g; ρ is specimen material density, g/cm³; S is the geometric area of contact, cm²; L is friction path, cm.

The structure was studied on a JEOL JEM-200CX transmission electron microscope with the use of mechanical and electrolytic foil thinning. Microhardness was determined on a Shumadzu HMV-G21DT device with a load on the indenter of 0.245 N by the residual imprint method. The phase composition of the specimens was determined on a Shimadzu XRD-7000 X-ray diffractometer in CrK_α radiation. Microindentation was performed on a Fischerscope HM2000 XYm measurement system according to ISO 14577, with a maximum load on the Vickers indenter of 0.245 N. The friction surfaces were examined on a Tescan VEGA II XMU scanning electron microscope.

RESULTS AND DISCUSSION

According to the data obtained from transmission electron microscopy, the initial structure of the quenched 03Cr16Ni14Mo3Ti steel is represented by large polyhedral austenite grains with the presence of individual unsplit dislocations and dislocation clusters (Fig. 1a). Severe plastic deformation occurring under frictional treatment results in severe dispersion of the structure in a thin (5 to 10 μm) surface layer of the austenitic steel; namely, nanocrystalline (with a crystalline grain size below 100 nm and large-angle boundaries) and submicrocrystalline (with a crystalline grain size exceeding 100 nm) austenitic structures (Fig. 1b, c) emerge. The X-ray phase analysis of the steel after FT has shown that the volume fraction of strain-induced martensite on the surface is at most 2 vol%. Thus, the steel is strain-resistant even under conditions of severe plastic deformation caused by FT in the surface layer.

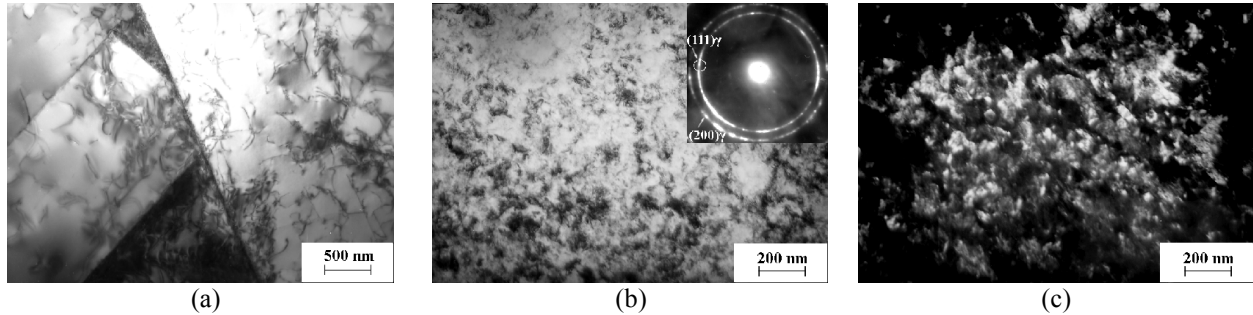


FIGURE 1. The structure of the surface layer of a 03Cr16Ni14Mo3Ti steel specimen in the initial quenched state (a) and after FT (b, c): light-field images (a, b), a dark-field image in the $(111)\gamma$ reflection (c)

As a result of FT, the microhardness on the surface of the 03Cr16Ni14Mo3Ti steel increases from 270 HV 0.025 to 720 HV 0.025. According to [1, 2], with FT, the hardening of the surface of the metastable 12Cr18Ni10Ti steel with an initial hardness of 220 HV 0.025 reaches 710 HV 0.025 despite increased loading ($P=392$ N) and the number of scans ($n=11$). Consequently, FT provides the 03Cr16Ni14Mo3Ti steel with strain hardening not inferior to that of the metastable 12Cr18Ni10Ti steel, whose surface acquires 70 vol% of strain-induced α' -martensite after FT. This effective strain hardening of the 03Cr16Ni14Mo3Ti steel is favored by a high friction coefficient ($f=0.47$) when FT is performed in argon by a synthetic diamond indenter. This makes the value of accumulated plastic strain considerable, the essential contribution being made by the shearing component depending on the friction force (coefficient) [6].

Instrumental microindentation has demonstrated that, as compared to EP, nanostructuring FT of the 03Cr16Ni14Mo3Ti steel surface decreases the values of maximum and residual indentation depth h_{max} and h_p and increases indentation hardness under maximum loading H_{IT} and Martens hardness HM taking into account not only

plastic, but also elastic strains (Table 1). The work of inverse elastic indentation deformation W_e also increases, this being indicative of the high deformability of the nanostructured layer in the elastic region. On the contrary, the values of the total mechanical work of indentation W_i consisting of the work of plastic deformation and the work of elastic recovery decrease as a result of FT, since the hardened surface layer deforms less under the indenter. The contact elastic modulus E^* varies only within a range of 7%.

TABLE 1. The results of instrumental microindentation of the surfaces of 03Cr16Ni14Mo3Ti steel specimens

Treatment	$h_{max}, \mu m$	HM, GPa	E^*, GPa	$W_e \cdot 10^{-3} \mu J$	$R, \%$	H_{IT}/E^*	$H_{IT}^3/E^{*2}, GPa$	δ_A
	$h_p, \mu m$	H_{IT}, GPa		$W_i \cdot 10^{-3}, \mu J$				
EP	1.74±0.09	2.9±0.3	205.6±25.4	19.9±1.4	9.7	0.016	0.001	0.86
	1.57±0.13	3.4±0.4		145.8±9.8				
FT	1.23±0.07	5.5±0.6	192.4±15.0	31.5±1.6	22.0	0.038	0.011	0.69
	0.98±0.09	7.3±0.9		103.8±8.2				

Parameters determining the ability of the surface layers to resist mechanical contact action were calculated from the results of microindentation. It follows from the data presented in the table that FT increases the ratio of indentation hardness to the contact elastic modulus H_{IT}/E^* [7] and elastic recovery $\%R=((h_{max}-h_p)/h_{max}) \times 100\%$ [8]. These parameters characterize elastic strain (the share of elastic strain in the total strain) and, consequently, the ability of the steel to resist an action without plastic deformation. The ratio H_{IT}^3/E^{*2} increases even more (by an order of magnitude). This ratio is conventionally considered a characteristic of resistance to plastic strain, since it is proportional to material flow stress P_y [9]. Consequently, FT substantially increases the ability of the surface layer to withstand contact loads without plastic deformation even after the onset of plastic flow. The values of the plasticity index $\delta_A=1-(W_e/W_i)$ [10] characterizing material plasticity by the share of plastic strain in the total elastic-plastic strain decrease only by 20% after FT (Table 1).

Testing under conditions lubricated sliding friction has shown that the 03Cr16Ni14Mo3Ti steel after FT is characterized by 4 to 10 times as low values of wear intensity as compared to the initial undeformed state (Fig. 2a). The friction coefficients f range between 0.11 and 0.12 in all the tests. This corresponds to the conditions of boundary friction ($f \leq 0.14$), when the friction of two solids occurs in the presence of fluid on the friction surfaces [11].

The examination of the wear surfaces has shown that plastic edging (predeformation) of the metal intensively develops on the friction surface of the steel after EP and that the wear occurs in the form of low-cycle friction fatigue [11] with the separation of large fragments (Fig. 2b). FT restricts drastically the processes of plastic edging (Fig. 2c). On the friction surface there appear separate smoothed areas where elastic edging prevails under friction loading. As is known [11], when there is elastic edging resulting from multiple deformation within elastic strain, fatigue wear develops (high-cycle frictional fatigue), which is characterized by low values of wear intensity. As a result of restricted processes of plastic edging after FT, the wear intensity of the steel in the tests for lubricated sliding friction under the loads $P=392-588$ N decreases to $I_h=(1.3-4.0) \cdot 10^{-9}$, see Fig. 2a.

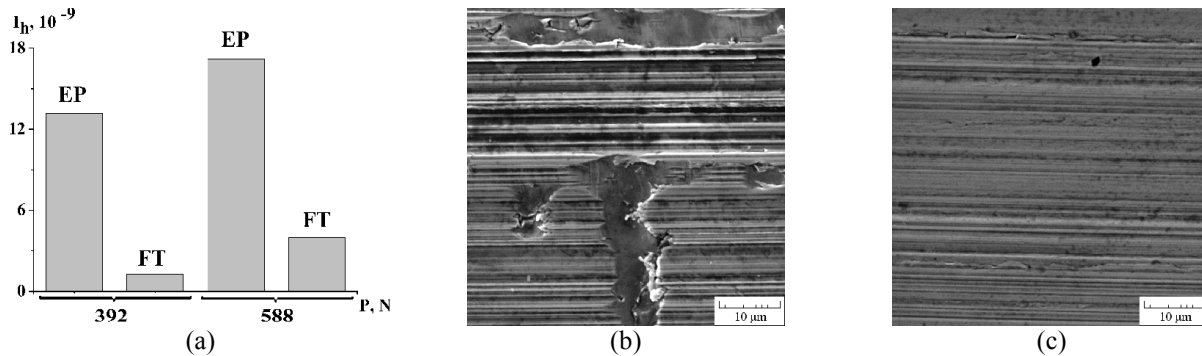


FIGURE 2. Wear intensity I_h (a) and the wear surfaces (b, c) of 03Cr16Ni14Mo3Ti steel specimens in the initial state after EP (b) and after FT (c) tested for lubricated sliding friction against steel 45 under the loads $P=392$ N (a) and $P=588$ N (a, b, c)

The observed restriction of the processes of plastic edging in the FT-hardened steel in tribological testing is attributed to the formation of a surface layer with nano- and submicroscopic austenitic structures during FT (see Fig. 1b, c) and, according to the microindentation data shown in the table, increased resistance to plastic deformation under contact loading. Thus, for the stable austenitic Cr-Ni steel subjected to nanostructuring FT, the processes of elastic-plastic deformation of a thin surface layer, controlled by the method of instrumental indentation, have been related to wear mechanisms governing wear resistance. The relation of microindentation results to the wear resistance of FT-hardened surface layers under different wear conditions (abrasive, adhesive, fatigue) was substantiated earlier in [12, 13] for martensitic steels and in [1] for metastable austenitic steel.

CONCLUSIONS

Frictional treatment (FT) of the 03Cr16Ni14Mo3Ti strain-resistant austenitic steel with a sliding indenter gives rise to the formation of fragmented submicro- and nanocrystalline austenitic structures with a hardness of 720 HV 0.025 in the surface layer.

Nanostructuring FT offers a 4-fold increase in wear resistance under conditions of boundary friction (in testing for lubricated sliding friction) due to restricted processes of plastic edging on the hardened surface. According to the microindentation data, these changes in the wear mechanism result from the increased ability of the nanostructured layer to deform under mechanical contact action predominantly in the elastic region and to resist the development of plastic flow.

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